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16TH NORTH SEA FLOW MEASUREMENT WORKSHOP 1998

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1 INTRODUCTION

It is said that necessity is the mother of invention but several necessities had to come together for the development of ESMER (Expert System for Multiphase Flow Regime Identification and Metering). The first was the need to work within a low budget in setting up a new laboratory at Imperial College in 1986. The brief was to set up a multiphase laboratory and conduct a research programme in topics which are of interest to the oil industry. One topic which appeared to be of interest to the oil industry was multiphase flow metering. A commercially available multi-phase flow meter did not yet appear to be available. To stay within budget the team chose a development path based on simple off-the-shelf sensors and electronics, avoided spool designs more complicated than a straight piece of pipe (no mixers) and placed maximum emphasis on modeling the natural features of multiphase flow by software. At this time Personal Computers were just beginning to offer adequate power for on-line digital signal processing. The strategy to keep hardware simple and to build a flow meter with standard off-the-shelf components has remained to date.

The second necessity was the long term requirement from Shell Expro for low cost, high performance multiphase meters. It was evident that the major benefit to Shell Expro from multiphase meters would come when it was practical to use them to allocate production from several operators feeding into common facilities. When approached by Imperial College in 1989 to co-sponsor further ESMER development, Shell Expro saw the potential of the technique, but asked that another two guiding principles be followed. A multiphase meter using simple hardware was to be developed as a low cost meter in its own right, but the signal processing electronics was to be kept sufficiently general that there would be the possibility of enhancing the performance of other manufacturer's meters without having to change out the hardware. Shell Expro has remained the largest industrial sponsor for ESMER.

The third necessity was a metering system supplier willing to participate in field prototype development and commercialisation. By 1995 ESMER was in danger of becoming yet another good idea that failed to reach the market. The concepts involved in ESMER were perceived as being quite strange and were not readily received by companies who considered measurement from a mechanical viewpoint, rather than a signal processing one, Companies already working on multiphase meters had enough to do in developing their own ideas. Spectra Tek (later bought by Daniel Industries) wanted to be involved in multiphase metering, but did not wish to develop expensive hardware. They had set up a subsidiary company for marketing complete metering systems that was an ideal vehicle for developing field prototypes.

This paper describes the first field prototype flow meter which has been working at Shell's Auk Platform since July 1997 and discusses the tests that have been carried out to establish its performance.

2 MULTIPHASE FLOW

It is necessary to take a brief look at the fundamentals of multiphase flow to understand the ESMER methodology.

There have been two fundamentally different schools of study of multiphase flow. The traditional school began by visual observation of the flow aiming to construct a universal flow regime map [1]. For reasons described next, an unequivocal a-priori determination of the flow regime was central to the traditional approach.

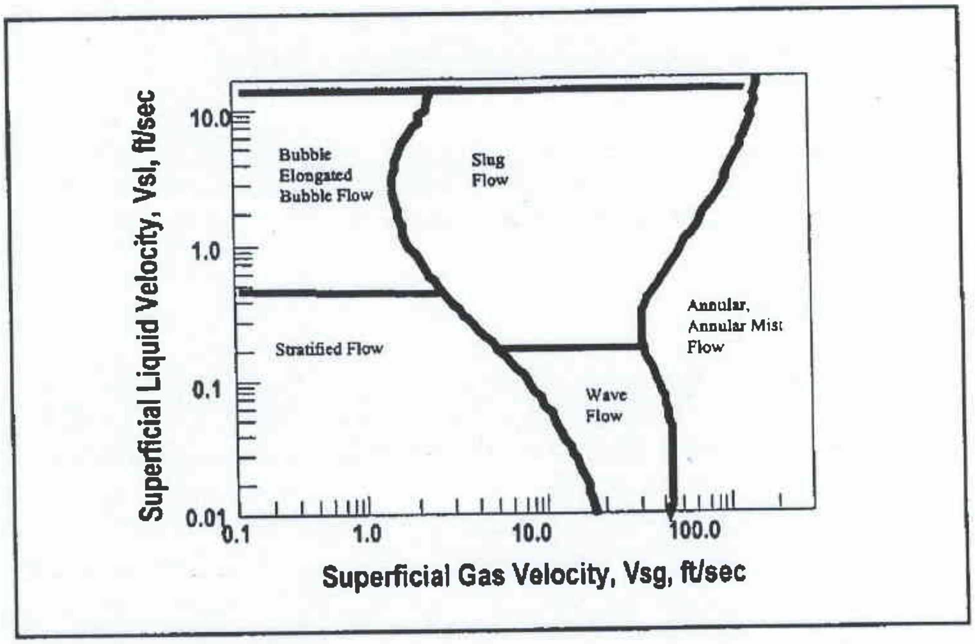


Figure 1 Mandhane Flow Regime Map

"Universalisation" was hampered not just by complex fluid behavior but also by the subjective nature of the visualisation effort and the language of the descriptions. "Wavy whist" flow regime can be cited as an extreme example. For mathematical modeling the traditional school adapted the theory of single phase fluid mechanics to multi-phase flow by adding adjustment coefficients into the deterministic Newtonian fluid mechanics models. Those serving engineering interests preferred the Bernoulli equation and those serving scientific interests the Navier Stokes equation as the foundation on which adjustments were applied. The reasons given for the adjustments were the characterisation of shear stresses between the phases in different flow regimes. For example, in bubbly flow these would be modeled one way, in annular flow in another way often with reference to a simplified and deterministic "wire diagram" of the flow regime.

A new school of multiphase investigators appeared in the late seventies provoked by new developments in sensors and electronics. These observed multi-phase flow at sampling frequencies matching the time scales of the turbulence in the flow and chose probabilistic methods for mathematical modelling of the observations [2, 3, 4, 5, 6, 7, 8, 9, 10].

3 EXPERT SYSTEM FOR MULTIPHASE FLOW METERING

This is when the team at Imperial College entered the foray. It was still early days of application of digital signal processing in multiphase investigations. Quite a number of our predecessors in the "new" school were equipped with analogue electronics analysers which gave them a limited range of mathematical capabilities. The precursor of ESMER was the freedom of mathematical analysis offered by the digitisation of the random time series of the turbulent hydrodynamic signals. The whole range of signal processing mathematics as applied from voice recognition to seismic analysis to medical science could now be imported off-the-shelf. An extensive programme of theoretical and laboratory investigations was conducted at Imperial College between 1986 and 1994 examining and classifying the random characteristics of multiphase flow by digital signal analysis methods [11, 12, 13, 14, 15, 16, 17, 18, 19].

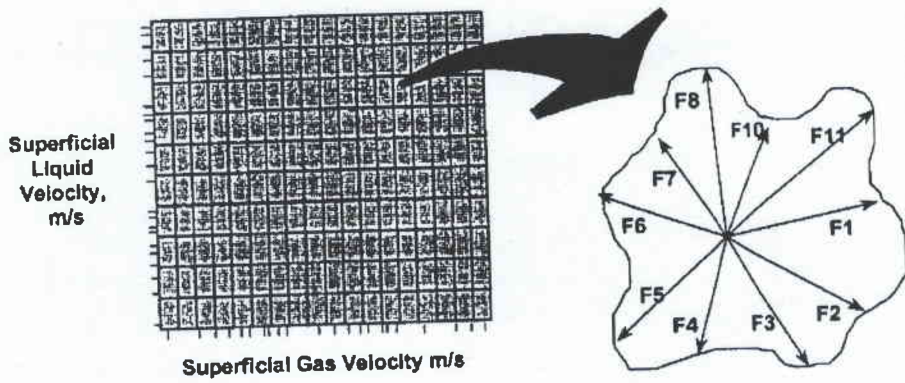


Figure 2 ESMER Feature Contour Map and Feature Vector Grid

The concept of ESMER can be generalised as "learning from experience". As a start one can classify the approach as an application of artificial intelligence to multiphase metering. To put it into context; ESMER learns that certain combinations of the flow rates of individual phases give rise to particular characteristics of the random turbulence signals. That is, ESMER characterises and classifies the properties of the turbulence signals in terms of the individual phase flow rates. When the experience is sufficiently mature and reproducible ESMER can begin "predicting" the flow rates from an observation of the characteristics of the random turbulence signals.

There are two further points which must be clarified on a conceptual level. First, one must "purify" the experience as manifested by the surrogates of the turbulence (i.e. the pressure signal). This means enhancement by feature extraction and filtering. Second one should assist the classification by human experience. A simple example of such experience is to "tell" the system that a certain observation is taking place in a horizontal flow line rather than a vertical flow line. It is this second point which has permitted us to call the methodology an "Expert System". The expertise of the human investigator can be and should be imparted into the model in many ways. For instance with reference to an operator's experience on a particular well or with reference to the legacy of classical fluid mechanics. ESMER has taken advantage of this legacy in selecting the "training targets".

To summarise the philosophy of ESMER and to define its distinctive character, we can say that ESMER is a flow measuring system that learns by example rather than being dictated by the conceptual and deterministic fluid mechanics models.

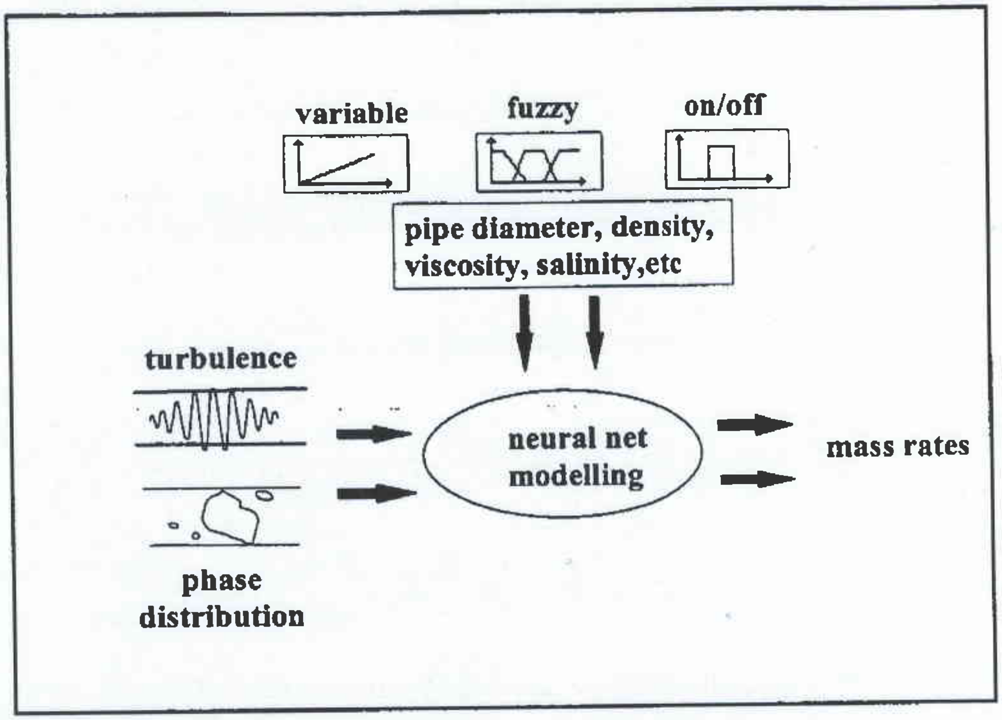


Figure 3 ESMER Conceptual Model

4 EQUIPMENT

The prototype flow meter (named AukESMER) comprised a non-intrusive 4 inch diameter pipeline spool of 2m length fitted with high frequency pressure sensors (Druck and Statham) and impedance sensors (Meridian). The spool was assembled by Daniel Europe Ltd.

The electronics comprised an impedance meter (PSL) and a PC (Gateway) fitted with a multi-channel A/D. A software system developed by PSL ran on the PC Windows platform for sampling, analysis and graphical display of the measurements.

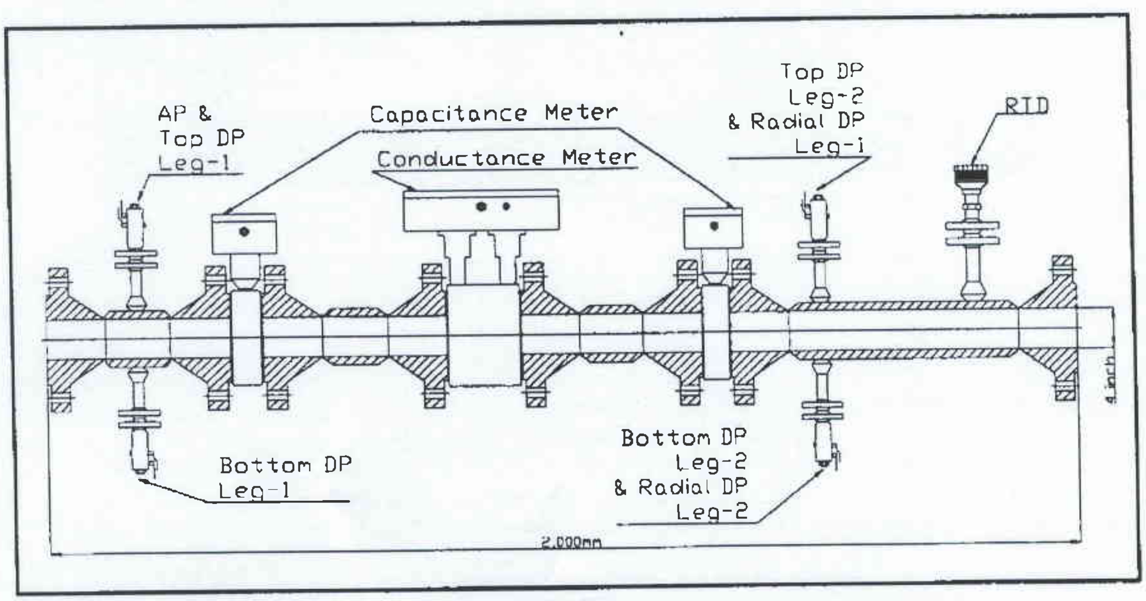


Figure 4 GA Drawing of Spool Piece

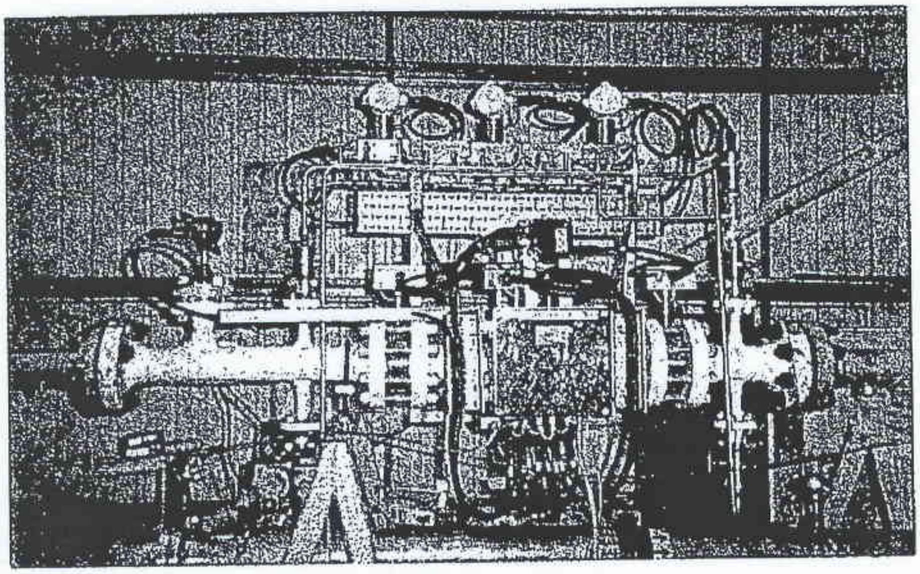


Figure 5 Photograph of Spool Piece

The signal sampling parameters were as follows: sampling frequency of 800 Hz, sampling period of 40.96 s, processing time of 30 secs. The measurement frequency was once every three minutes. A set of features were derived from AP, Top DP, Bottom DP, radial DP and conductance signals under the above sampling conditions.

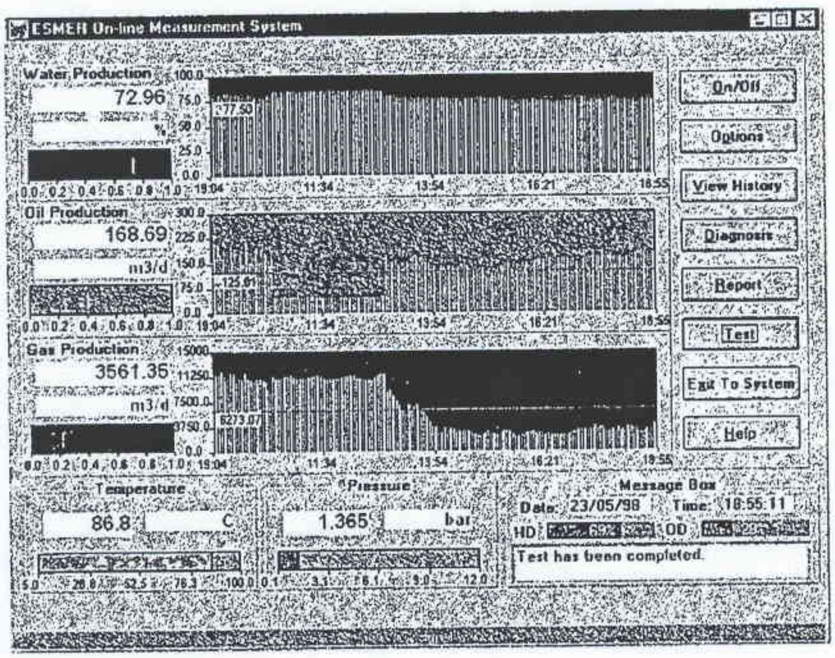


Figure 6 AukEsmer User Interface

A distinctive character of the equipment is that there is no flow conditioner which aims to impart on the equipment the "conceived" properties of an ideal flow regime. To the contrary, the equipment benefits from the "natural" occurrence of the flow regimes existing under a given set of pipeline and physico-chemical conditions.

This last statement gives rise to the justifiable concern that ESMER requires some in-situ calibration. This is true but the difference between ESMER and any other commercially available technique appears to be one of degree as we shall proceed to demonstrate.

5 CALIBRATION

The primary calibration of the system was conducted at the National Engineering Laboratory. Tests were conducted under the following range of conditions:

Water cut (25g/l $MgSO_4$ and 50g/l $MgSO_4$): 5% to 75%
Oil flow rate (Forties Crude/D80 Kerosene Mix 70/30): 0.2 to 4 m/s
Gas flow rate (Nitrogen): 0.4 to 20 m/s

The data samples were separated into two groups. One group was used for calibration and the other for testing.

The calibration procedure was as follows. A set of features were derived from each sensor, an optimum feature set was selected and a back propagating neural net was trained against reference measurements of the flow rates of individual phases.

The test procedure was as follows. The test group of samples were passed through the neural net predictor algorithms and the result of the predictions were compared against the recorded reference (single phase) measurements for those test points. The results are shown in the following figures. Relative error is defined as (Measurement - Actual) / Actual.

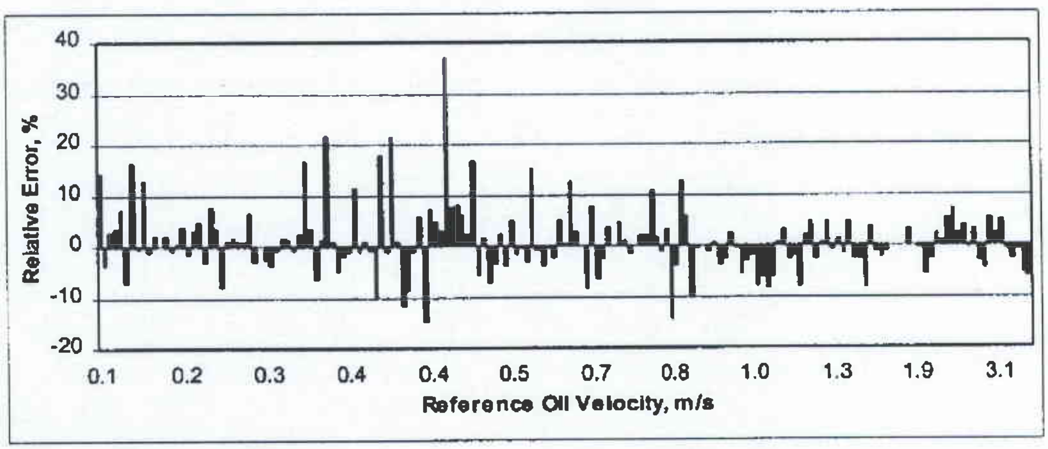


Figure 7 Oil Velocity Relative Accuracy

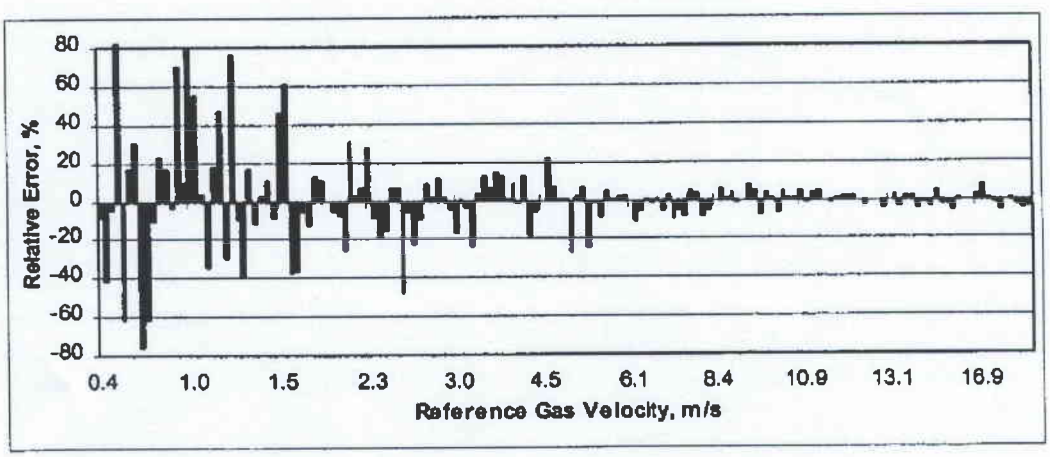


Figure 8 Gas Velocity Relative Accuracy

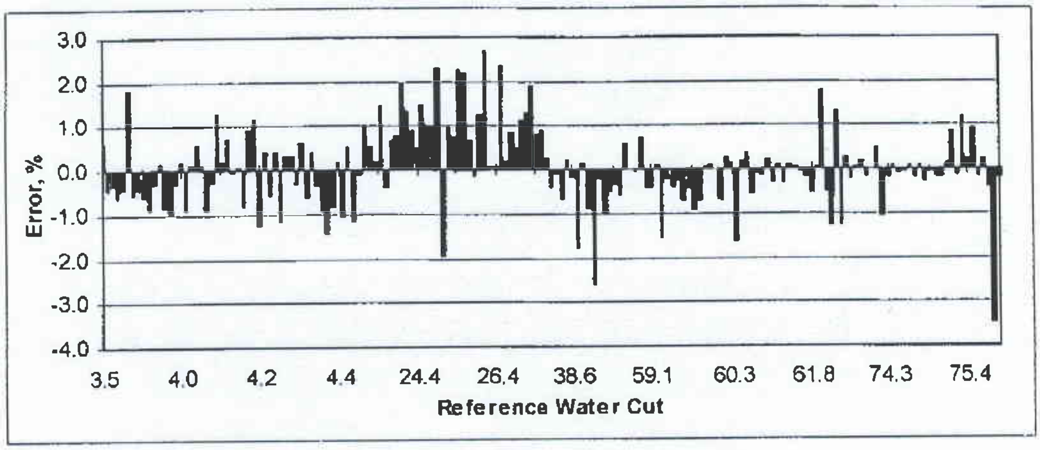


Figure 9 Water-Cut Accuracy

The next figure shows the statistical distribution of error. The scatter is symmetrical and the resulting average (e.g. daily) flow rate should exhibit a smaller error than individual measurements.

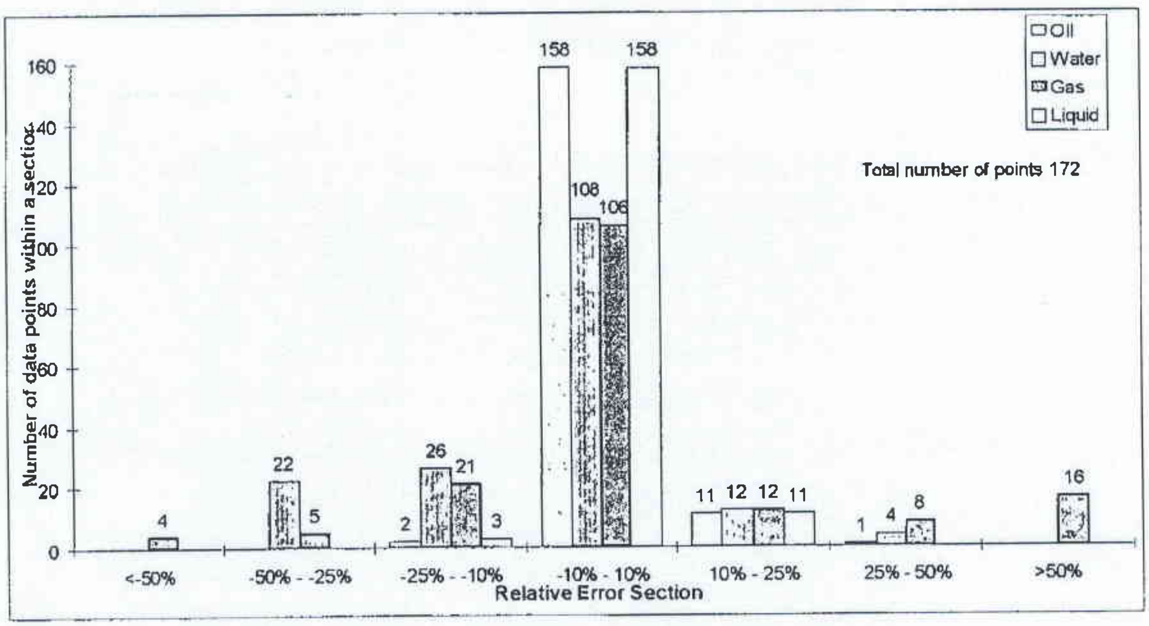


Figure 10 Statistical Distribution of Measurement Accuracy

6 FIELD TEST OVERVIEW

AukESMER was installed on the Shell Auk Platform in the North Sea in June 1997. The neural net obtained from the laboratory tests at NEL became the primary "factory" calibration with the intention for it to be "tuned" for field conditions (with as few in-situ measurements as possible). On the first two trials in July and October 1997 no secondary reference measurements were available to execute this strategy. The meter was left in an operational condition gathering original turbulent data samples which were shipped to base for analysis on a regular basis.

The first quantitative field re-calibration and tests took place between 29 April and 4 May 1998. During these tests a production separator was dedicated to the well. It was run by the platform supervisors and TracerFlow measurements were carried out by SGS Redwood to provide the reference flow rates. Three reference points were collected at 100, 75 and 50 percent of the full operational flow rate. The flow rate was controlled by varying the water injection rate into the well. Water-cut reference was measured by base sand and water (BS&W) measurements well. Water-cut reference was measured by base sand and water (BS&W) measurements collected on an hourly basis. The gas flow rate was measured by an orifice located at the gas outlet of the low pressure (LP) separator, and the oil flow rate was measured by a turbine located at the oil outlet of the low pressure (LP) separator. Within the time permitted on the platform, the ESMER factory calibration was re-tuned with the inclusion of two points drawn from the separator measurements at 100 and 75% flow rates.

Upon return to base, a detailed program of study was started to analyse the extensive data gathered from the platform to develop / propose more advanced methods for fine tuning the factory calibration. In the first stage of the study, the factory calibration was re-tuned by drawing data from three flow conditions described qualitatively as 100%,75% and 50% of the full operational conditions. The tune up data was drawn from measurements conducted on a single day (1.5.98) and constituted a sparse contribution to the factory calibration database.

Measurements were then simulated for three days of operation (two days of which is independent of the data used in tuning up the calibration) and compared with the average reference measurements. This means a moving average of one hour against the separator and ten minutes against the tracer. Under stable operating conditions ESMER matched the separator and the tracer measurements with an accuracy of better than ±10 percent. The match was better than ±15 percent at low flow rates. The disagreement is thought to be largely due to the instability of the flow conditions at low flow rates where large changes were observed in the flow rates over the respective averaging periods.

On-line record of measurements taken by ESMER, updated every three minutes, show that ESMER correctly trends the changes in the flow rates in real time. As these changes were imposed by the operators cutting down on water injection rate into the well, there is an accurate time log of the expected changes. These accord very well with ESMER's predictions.

7 FIELD TEST DETAIL

7.1 Reference measurements

Reference flow rates were provided by the operators from a separator and by the service company, SGS Redwood, from a TracerFlow technique.

The separator sampling conditions were:
- Time weight average oil production rate (equivalent to "bucket and stop watch method") over 0.5 or 1 hour.
- Time weight average water flow rate from Bs&W and oil production rate as above.

TracerFlow sampling conditions were:
"Snap-shot" measurement of the oil /water production rate every ten minutes.

7.2 Test procedure

The time table of the events and numbers of samples collected during the calibration process is summarised on the next table. The tests were conducted in three phases by successively cutting down on the production rate by reducing the water injection rate into the well. These are referred to as Phase A-100%, B-75%, C-50% of full operational conditions with a period of change / stabilization in between. The percentage stated here is an intended effect of the cut back. In reality, the calibration and testing exercise was based on the on-line reference measurements obtained from the separator and tracer flow. These measurements do not in fact corroborate the intended cut-back but the % labels are retained for ease of reference.

Table 1 - Summary of Calibration Reference Measurements

Date/Time 1 May 1998	Production Condition As a "Notional" % of Operational Flow	Number of Separator Samples	Number of Esmer Samples	Number of Tracer Samples
12:00 - 15:00	100 %	3	52	10
15:00 - 16:30	reducing flow rate stabilisation time		24	
16:30 - 19:00	75%	4	33	10
19:00 - 20:00	reducing flow rate stabilisation time.		7	
20:00 - 22:00	50%	6	38	

7.3 Tuning the factory calibration

For the Liquid / Gas Neural Net the training data set (the calibration database) comprised 50 factory points and three field measurements obtained on 1 May 1998 at 100, 75 and 50 percent flow rate data. For the Water Cut Neural Net the training data set comprised 133 factory points and three field measurements on 1 May 1998 at 100, 75 and 50 percent flow rate data. The in-situ calibration requirement exemplified in this study, which we believe shall prove to be typical for ESMER, does not appear to be more demanding than the requirement faced by other multi-phase flow meters. In due course, the learning concepts underlying ESMER should in fact aid to reduce the in-situ tuning requirement further. This will be achieved with reference to a universal database of multi-phase flow characteristics maintained at base.

7.4 ESMER vs Separator

We begin with tests conducted on 1 May 1998. While the training and test data overlap for this date, the range of data and observations offer greater variety and a better opportunity for verification of the compliance of ESMER with trends than the observations and measurements made on the preceding two dates. Besides, TracerFlow measurements are only available for this day.

The tests were conducted in three stages by successively cutting down on the production rate by reducing the water injection rate into the well. These are marked as Phase A-100%, B-75%, C-50% of full operational conditions with a period of change / stabilization in between. The following charts show the results of the predictions point by point every three minutes (with a moving average of 5 points / 15 minutes) between 12.01 and 22.30 hours. (The gap between 19:00 and 20:00 is due to a shut down of the sampling procedure). It is seen that ESMER trends the known variations extremely well for all three phases. These are reported individually in turn.

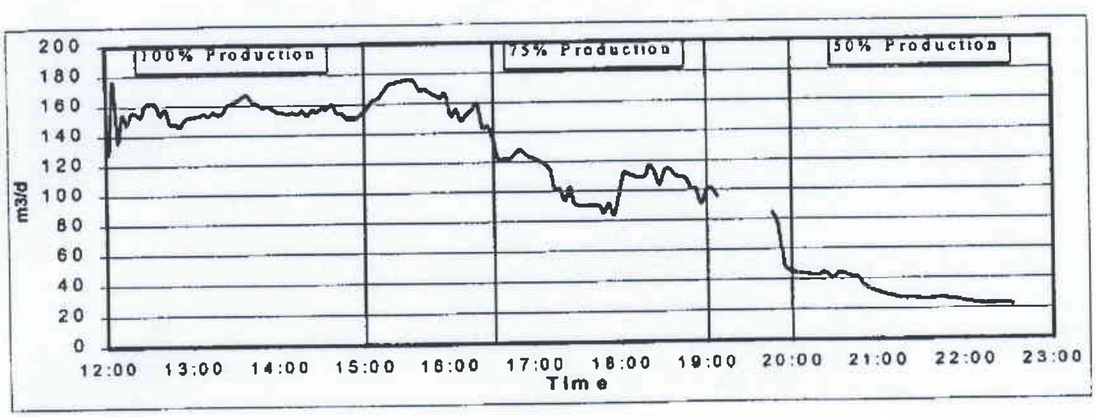


Figure 11 Oil Production at Well AA06 on 01/05/98

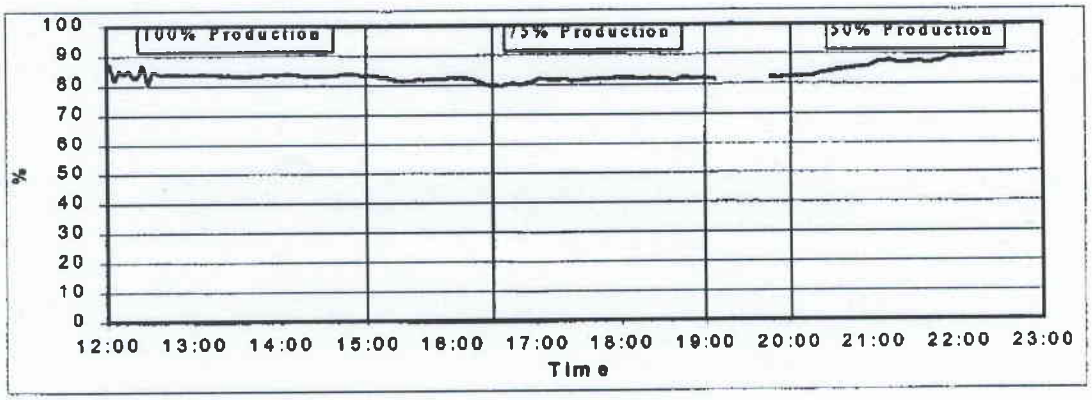


Figure 12 Water Cut Measurement at Well AA06 on 01/05/98

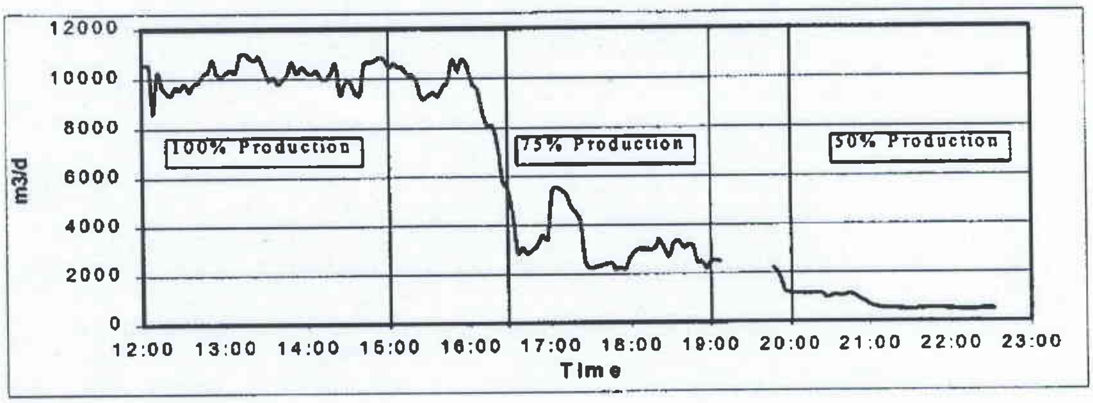


Figure 13 Gas Production at Well AA06 on 01/05/98

The results of tests for 30 April 1998 are reported next. On this day well AA06 was connected to the LP separator and measurements were taken on an hourly basis from 8:00 to 10:00 at "100% of full production" and from 10:00 to 12:00 at "50% of full production". The results shown in following diagrams are in excellent agreement with the known trends.

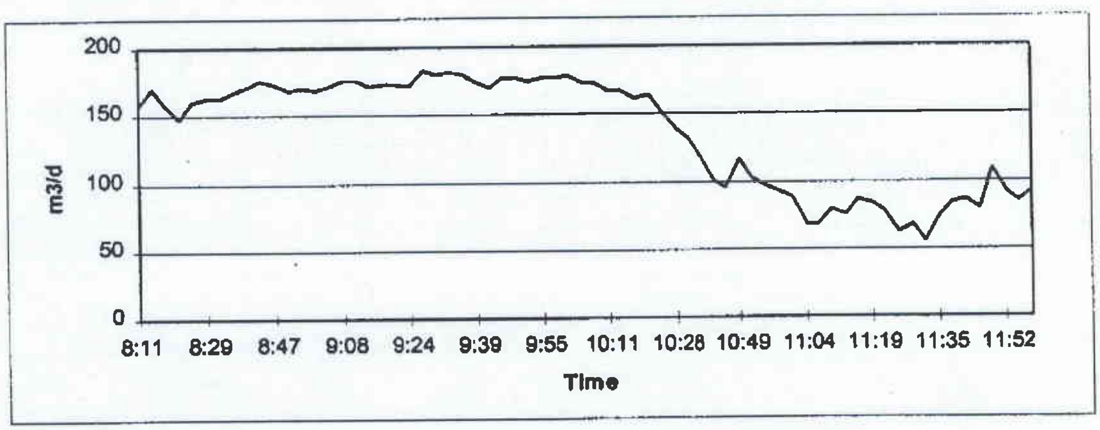


Figure 14 Oil Production at Well AA06 on 30/04/98

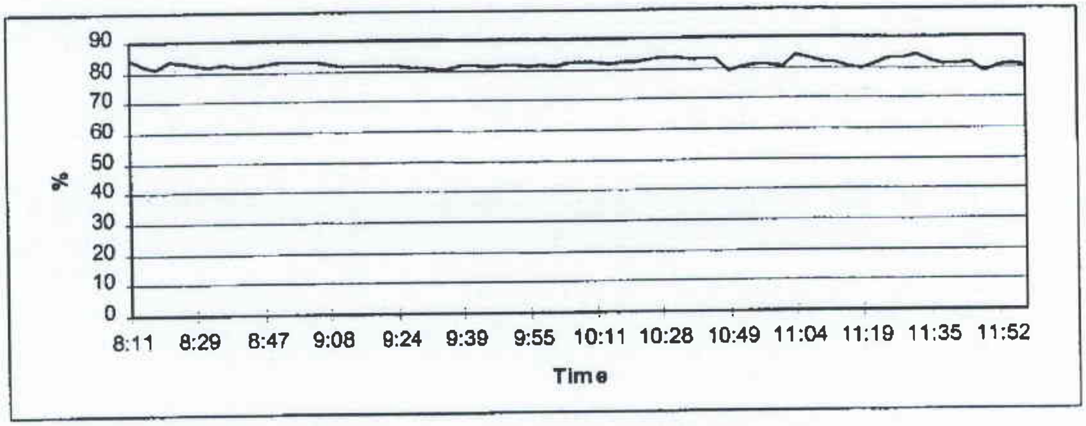


Figure 15 Water Cut Measurement at Well AA06 on 30/04/98

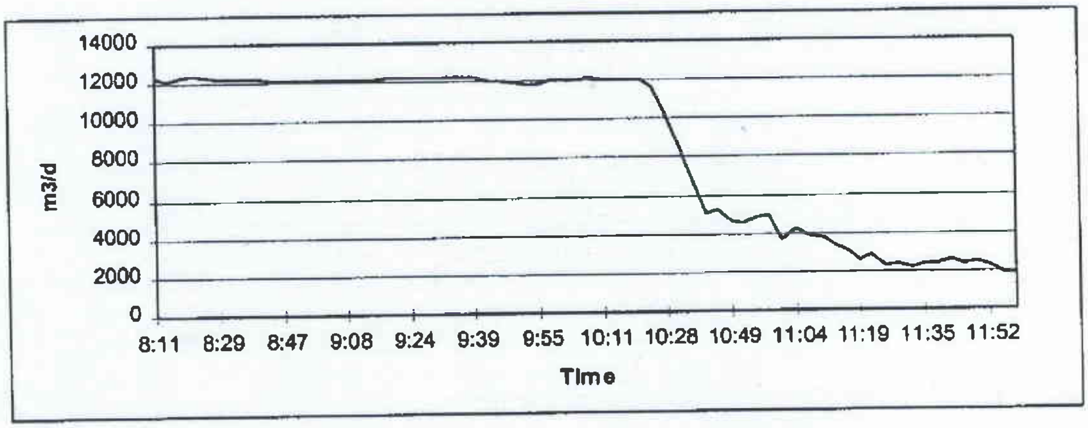


Figure 16 Gas Production at Well AA06 on 30/04/98

7.5 Average measurements

Flow rates predicted by ESMER every three minutes were evaluated against the reference measurements provided by the separator over an averaging period dictated by the separator. Separator measurements were obtained every hour, compared with every three minutes for ESMER and every ten minutes for TracerFlow. Thus a comparison was facilitated by averaging ESMER's predictions and the TracerFlow measurements over the course of one hour. The deviation between the average oil flow rates measured by ESMER and the Separator over the three stages of the tests are summarised in the table below.

Table 2 Comparison of Average Measurements over a Period of Observation ESMER vs Separator

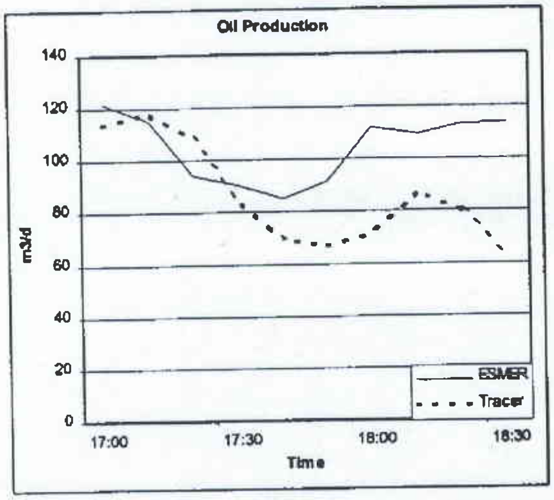
Date/Time 1 May 1998	Production Condition As a "Notional" % of Operational Flow	Deviation (ESMER-Separator) /ESMER*100% Oil Flowrate	Deviation (ESMER-Separator) /ESMER*100% Water Cut	Deviation (ESMER- Separator) /ESMER*100% Gas Flowrate
1May 12:00 - 15:00	100 %	-4.5%	0.6%	-4.1%
16:30 - 19:00	75%	+6.1%,	-1.5%	n/a
20:00 - 22:00	50%	+14.9%	-0.2%	n/a
30Apr 9:00 - 10:00	100 %	+1.2%	-1.2%	+0.5%
11:00-12:00	50%	-6.4%	n/a	+60%
29 Apr 15:00 - 19:00	100 %	8.3%	-0.7%	2.8%

A large discrepancy was observed for gas flow rate on 30 April. We believe that this is simply due to the mis-match between the averaging periods of the two measurement systems when the flow conditions have not yet stabilised. For example, at 10 am, when ESMER averaging process starts (for the 11 am average at 7905 m^3/d), the gas flow rates is still at the initial full production level.

7.6 ESMER vs TracerFlow

First a few words about the Tracer Technique itself. Two types of chemicals (fluorescent dyes) are injected into the well head. One dye is soluble in oil and the other is soluble in water only. The injection continues at a constant rate for about 100-120 minutes. The technique requires approximately 100 pipe diameter distance between injection and sampling points for complete mixing. Since it is impossible to find a straight pipe section of this length on platform, the distance was kept shorter with the assumption of complete mixing of the dyes with the individual oil and water phases considering the effect of several bends on the way. The sampling point was set at about 4-5 m downstream of ESMER spool. The samples were collected by leaking flow into test tubes at 10 minute intervals during a 90 minute period. The samples were given 3-4 hours for separation and then analyzed under fluorescent light to detect the amount of dye in each phase. The main disadvantage of the technique is that it requires stable and homogenous flow. The slug flow regime does not produce reliable results.

The benchmark tests were based on the same calibration system described above. That is, the TracerFlow data was not used in the calibration exercise up to this point. However, it should be said that there is no fundamental objection to using the TracerFlow measurements in the primary factory calibration /re-tuning of the ESMER system (under those flow regimes where it works). In principle TracerFlow should offer a better spatial and temporal match for the characterisation of the flow conditions in the pipeline than the separator. As shown on the diagrams below the TracerFlow measurements were obtained every ten minutes and they facilitate a comparison between TracerFlow and ESMER drawn on a ten minute averaging period.



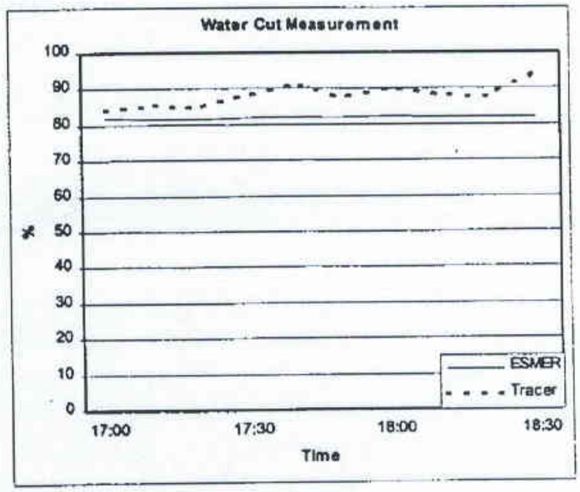


Figure 17 Comparison of ESMER vs TracerFlow at 75% production

The next table summarises the average deviation between the two measurement systems. The average is applied as an arithmetical average of measurements taken every ten minutes over the full course of the two stages of the tests labeled as 100% and 75% production conditions.

Table 3 Average Deviation between ESMER vs Tracer

Ref	Date/Time 29 Apr 1998	Production Condition As a "Notional" % of Operational Flow	Deviation (ESMER- Tracer) /ESMER*100% Oil Flowrate	Deviation (ESMER- Tracer) /ESMER*100% Water Cut
A	13:45 - 15:15	100%	-6.3%	-3.2%
B	17:00 - 18:30	75 %	17.4%	-7.8%

8 CONCLUSIONS

The ESMER approach to multiphase metering, using simple sensors and complex signal processing, can be readily applied in oil field applications. However, there are relatively few people at present with a feeling for how the ESMER approach works. This has been the main difficulty in promoting ESMER during its development to date.

The system tested on Auk, comprising a straight pipe with off-the-shelf pressure and impedance sensors, gives results which bear good comparison with any available multiphase meter. The accuracy of the meter is about 10-15% relative on all three phases.

Adjusting the laboratory derived meter calibration to field conditions proved relatively straightforward. A few field sample points based on the operators' experience were added to the laboratory data and the system was retrained.

The ESMER approach is particularly suited to low cost/medium accuracy applications, but there are no fundamental limits to the performance that can be achieved using this approach. This means that with improved sensors, and, more importantly, with better quality training data, high performance multiphase metering is perfectly feasible without significant increase in hardware costs.

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